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INITIATION OF NON-TROPICAL THUNDERSTORMS BY SOLAR ACTIVITY

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Correlative evidence accumulating since 1926 suggests that there must be
some physical coupling mechanism between solar activity and thunderstorm oc-
currence in middle to high latitudes. Such a link may be provided by alteration
of atmospheric electric parameters through the combined influence of high-energy
solar protons and decreased cosmic ray intensities, both of which are associated
with active solar events. The protons produce excess ionization near and above
20 km, while the Forbush decrease causes a lowered conductivity and enhanced
fair-weather atmospheric electric field below that altitude. Consequent effects
ultimately lead to a charge distribution similar to that found in thunderclouds,
and then other cloud physics processes take over to generate the intense electric
fields required for lightning discharge. The suggested mechanism appears plaus-
ible enough to warrant a coordinated experimental effort involving satellite,
balloon and ground-based measurements of the forcing functions (solar protons

and cosmic rays) and the responding atmospheric electrical and ionic species'

characteristics.

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ILLUSTRATIONS (Continued)

INITIATION OF NON-TROPICAL THUNDERSTORMS

BY SOLAR ACTIVITY

1. INTRODUCTION

There is presently a resurgence of interest in sun-weather relationships as

evidenced by the publication of an extensive bibliography (Shapley, et al., 1975)

and several reviews (e.g., Wilcox, 1975; King, 1975) on the subject, and by a

number of special conferences (e.g., a symposium on "Possible Relationships

Between Solar Activity and Meteorological Phenomena" at NASA/Goddard Space

Flight Center, November, 1973; a session on "Solar Variability and Meteoro-

logical Response" at the 55th Annual AMS Meeting in Denver, January, 1975;

sessions organized by W. O. Roberts at the 16th General Assembly of the Inter-

national Union of Geodesy and Geophysics at Grenoble, August, 1975; sessions

at the International Symposium on Solar-Terrestrial Physics at Boulder, June,

1976). Two overriding conclusions seem to have emerged from these activities:

(1) consideration of the results of historical and contemporary observational and

statistical analyses suggests that there probably are some connections between

changes on the sun and changes in the lower atmosphere; (2) there has been a

singular lack of acceptable physical mechanisms to explain those probable

connections.

In response to the second conclusion, the intent of this paper is to present a

physical explanation for just one of the meteorological phenomena reported to be

correlated with solar activity, with the hope that it, along with recent suggestions by Roberts and Olson (1973) and Dickinson (1975), may stimulate searches for additional linking mechanisms to explain some of the many reported correlations. If several such mechanisms can be identified, the subject of sun-weather relationships will be on much firmer ground, and improved predictions of weather and climate may in fact become achievable. If no acceptable mechanisms are found, interest in the subject is almost certain to wane again, and another hundred years of controversy (Meadows, 1975) may well reign. In the following, an attempt is made to establish a physical link between thunderstorms and solar variability.

That such a link may possibly exist has been demonstrated by several statistical analyses. On a long-term basis, a strong positive correlation (+0.88) has been found between sunspot number and thunderstorm occurrence frequency in Siberia (Septer, 1926; Brooks, 1934; Markson, 1971), which has held true over at least 5 solar cycles (~55 years) and cannot be ignored There is also evidence for the same correlation for thunderstorms in Norway (Schou, 1932), Japan (Noto, 1932), the West Indies (Brooks and Carruthers, 1953), and in England (Stringfellow, 1974).

The data for Great Britain are illustrated in Figure 1, where 5-year running means of both annual mean sunspot numbers and an annual index of lightning incidence defined by Stringfellow (1974) are shown. Although there are year-to-year
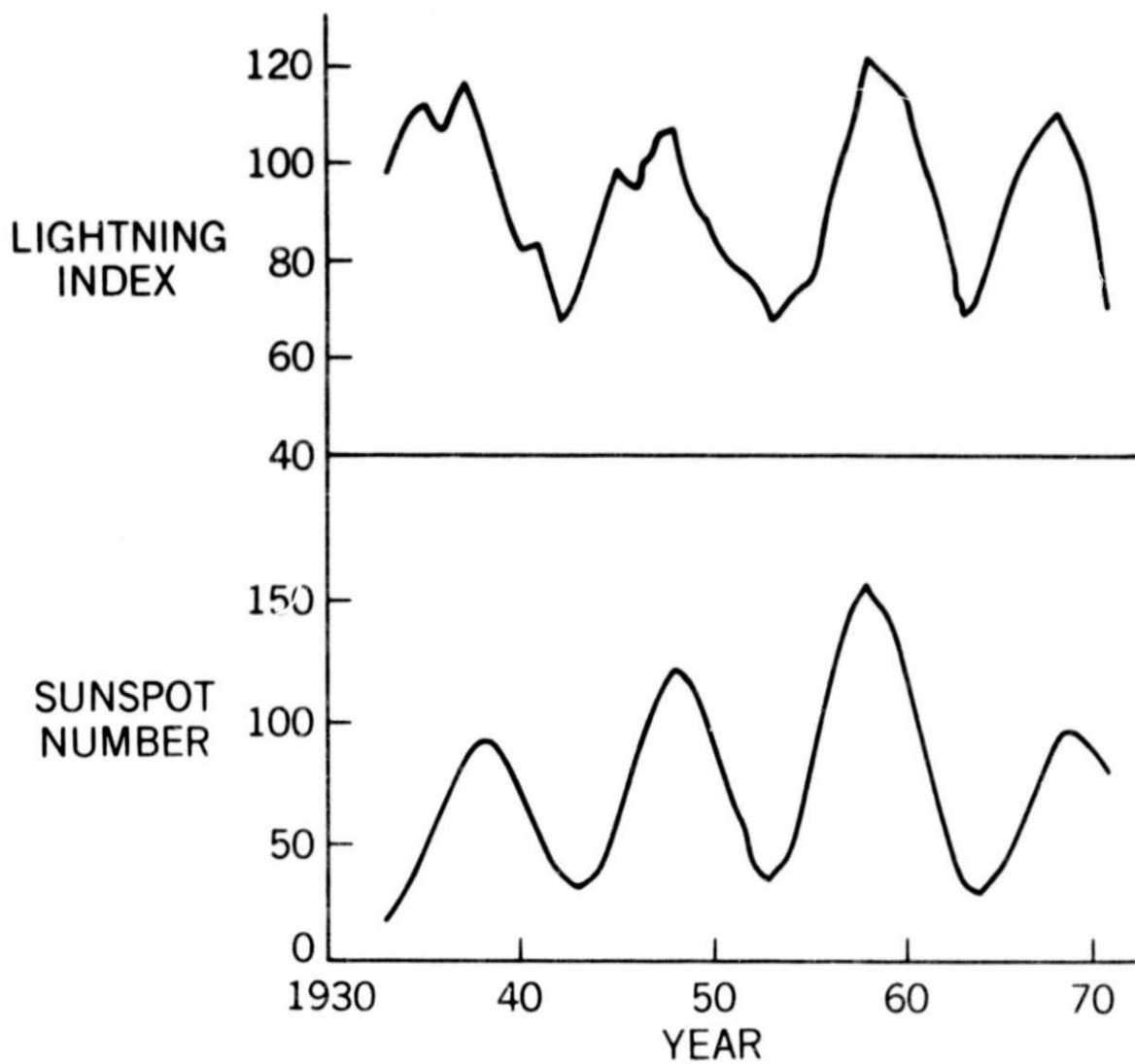
Figure 1. Annual variation of 5-year running means of lightning incidence and sunspot number (after Stringfellow, 1974).

variations in the lightning index, there is a strong cyclic variation which is in phase with the solar cycle and has an amplitude of ±30% of the mean. The correlation coefficient between these two curves is +0.8, a result which is statistically significant, according to Stringfellow. These results, and those for Siberia (Septer, 1926), indicate that the frequency of thunderstorm occurrence in years of minimum solar activity is augmented by processes associated with an active sun (as measured by sunspot number).

On the short term, Reiter (1969, 1971), Markson (1971), and Bossolasco et al. (1972), found increases in thunderstorm activity 3-4 days after the eruption of a major solar flare, and Flohn (1950, 1951) noted increases in thunderstorm occurrence frequency in central and northern Europe following central prime meridian passage of major active sunspot groups. Also Markson (1971) and Bossolasco et al. (1973) have found changes in regional thunderstorm activity following the passage of certain solar magnetic sector boundaries past the Earth, and Park (1976) has shown that the polar cap vertical electric field associated with global thunderstorm activity responds to sector boundary crossings.

These long- and short-term statistical results are compatible, since it is known that active sunspot groups are most likely to generate solar flares and solar proton events, and on the average more such events take place during solar maximum than solar minimum years.

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Noting that the intensity of galactic cosmic rays varies inversely with the solar cycle with increasingly greater amplitudes at higher latitudes, and that they are the prime cause of ionization in the lower atmosphere, Ney (1959) suggested that cosmic ray variations rather than a direct solar influence might explain the Brooks (1934) correlations. Additional support for a strong solar-related cosmic ray influence on short-term thunderstorm correlations is given by the fact that the galactic cosmic ray intensity decreases dramatically following solar flares (the Forbush decrease), and it decreases following the passage of a solar magnetic sector boundary past the Earth (Wilcox and Ness, 1965). It would appear then, that the previously reported results could just as well be interpreted as negative correlations between thunderstorm activity and cosmic ray intensity rather than positive ones with solar activity (Ney, 1959; Markson, 1971).

On the other hand, strong solar flare eruptions are accompanied by the emission of high-energy solar protons, the proton events occur more often in solar maximum than solar minumum years, and there is indirect evidence for solar proton emission near solar magnetic sector boundaries as indicated by increases in the magnetic activity index K_p (Wilcox and Colburn, 1972). The high-energy protons ($E \geqslant 300\,\text{MeV}$) penetrate to altitudes at and below about 20 km and produce ionization (Reid, 1974). Thus, the previously reported statistics could also be interpreted as being positive correlations between thunderstorm occurrence and solar proton enhancements.

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These two interpretations suggest that it may be the combination of proton enhancements and cosmic ray decreases which is important in triggering conditions conducive to non-tropical thunderstorm formation. In the next sections we therefore address the question of how the atmospheric electric parameters are altered by these two agents, and then use the results to postulate an initiation mechanism leading to thundercloud development. The mechanism is quite different from that proposed by Markson (1975), who suggested that the regulation of the electrical resistance between cloud tops and the ionosphere by solar influences might be the key.

2. ATMOSPHERIC ELECTRIC EFFECTS

Energetic protons emitted by the sun during large solar flares penetrate the Earth's atmosphere to various depths depending on energy spectrum, atmospheric density and terrestrial magnetic field shielding. For most strong events, the magnetic field effect is small for geomagnetic latitudes poleward of about 45°. The following discussion neglects magnetic field influence and therefore applies principally to high latitude regions. Any atmospheric electric effects that may be produced by the incoming protons can be considered to occur through alteration of the ionization distribution in the atmosphere.

Ion-pair production rates (Q) for representative solar proton events occurring in the period 1965-1969 have been reviewed by Zmuda and Potemra (1972). Their results serve to illustrate the various depths to which solar protons can

penetrate as a function of energy spectrum. The ionization rate profiles due to three events with relatively "hard" spectra are reproduced in Figure 2. Compared to the production rates for cosmic rays (Webber, 1962) during quiet times, it is evident that ionization due to the solar protons begins to dominate at altitudes of 20 to 30 km. Two additional Q profiles due to solar protons are contained in Figure 2, to demonstrate the effects of major events. The August 4, 1972 profile (curve 4) was derived from proton data reported by Kohl and Bostrom (1973). Their peak fluxes for protons with energy >20, >30, and >60 MeV were fitted to the form $J(>E) = J_0 \exp(-E/E_0)$ (Zmuda and Potemra, 1972), and the production rates as a function of height were calculated using the specific ionization rates given by Reid (1974). At the peak of the August 4 event, the proton ionization rate greatly exceeded that of cosmic ray background at 20 km altitude. Finally, a result reported by Masley et al. (1962) is shown as point 9.

For the September 29, 1961 event, data from Bryant et al. (1962), for proton energies >130, >340, and >600 MeV, were utilized to compute Q as plotted in Figure 2 (curve 5). In this case the energy spectrum follows the form $J(>E) = J_0 E^{-1.5}$ better than the exponential form used by Zmuda and Potemra. The much harder spectrum observed in the September 29 event would have penetrated deeper into the atmosphere than any of the other events, and produced ionization in excess of cosmic ray background at altitudes even below 10 km.
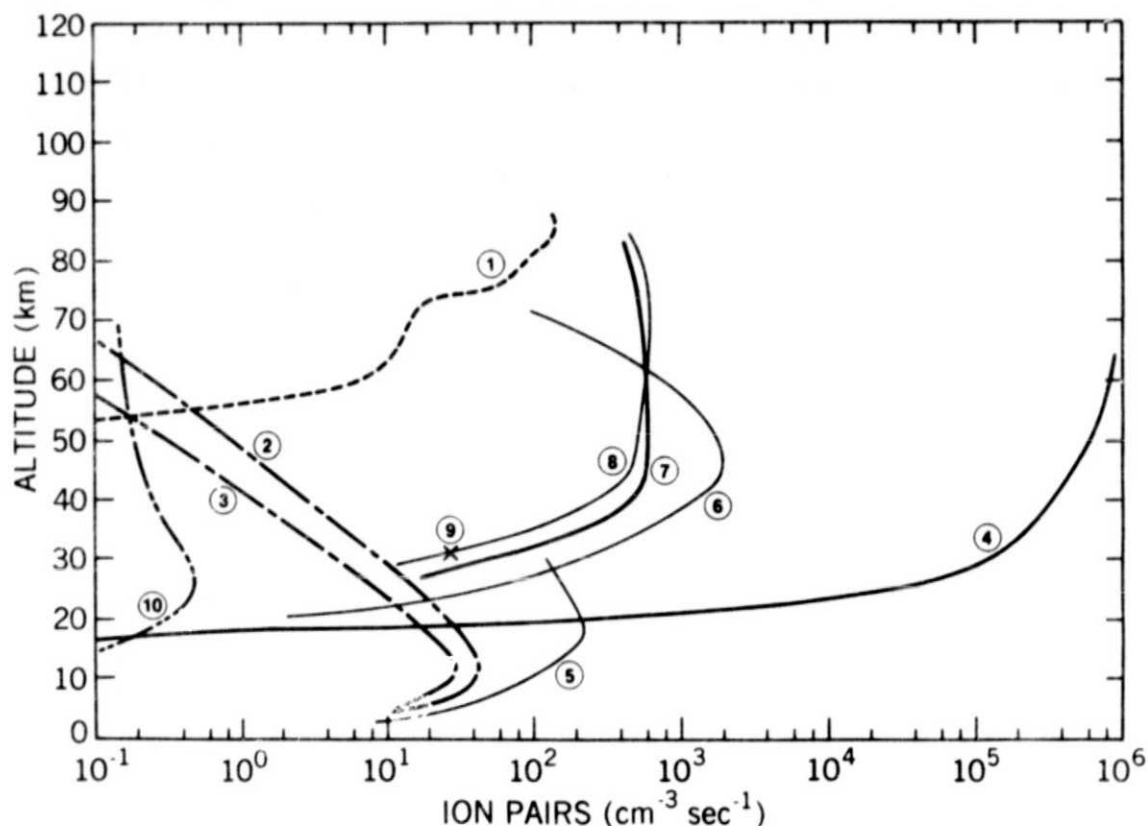
Figure 2. Ion-pair production rates for precipitating electrons (curve 1), cosmic rays in solar minimum (2) and solar maximum (3) years, and selected solar proton events (4 - August 4, 1972; 5 - September 29, 1961; 6 - November 2, 1969; 7 - November 18, 1968; 8 - January 28, 1967; 9 - single point for April 1, 1960) 10 - energetic bremsstrahlung from a typical auroral precipitation. Curves 6, 7, and 8 are from Zmuda and Potemra (1972); remainder derived from data given by: 1 - Larsen et al. (1976); 2, 3 - Webber (1962); 4 - Kohl and Bostrom (1973); 5 - Bryant et al. (1962); point 9 - Masley et al. (1962); 10 - Johnson and Imhof (1975).

The ionization due to precipitating electrons associated with auroral events generally exceeds that due to cosmic rays only at altitudes above about 60 km (see Zmuda and Potemra, 1972), but occasionally can be significant to about 55 km. An example is shown in Figure 2 (curve 1), where Q was derived from electron data reported by Larsen et al. (1976) over Ottawa, Canada. Curve 10 shows an associated x-ray bremsstrahlung ion-pair production profile for an unusually hard spectrum with a folding energy of 100 keV (Johnson and Imhof, 1975). The so-called "atmospheric electric equalization layer" or electrosphere, which may be defined at the height where the potential gradient falls to zero, is at an altitude of about 50 (Hake et al., 1973) to 60 km (Israel, 1970, p. 116). Thus, additional ionization produced by precipitating electrons and associated bremsstrahlung would not alter the height of the electrosphere and would not appreciably affect the ionization density at lower heights. One might therefore conclude that precipitating electrons would not affect standard atmospheric electric parameters, and those parameters would therefore not respond to "auroral events". It may be important to note that the positive effects of auroral events on the atmospheric electric field reported by Freier (1961) were observed at Minneapolis (geomagnetic latitude ~34°). At this latitude auroras are seldom seen, and then only in association with strong solar proton events. This suggests that the electric field changes noted by Freier were associated with energetic solar protons rather than with precipitating auroral electrons.

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The introduction of additional ionization at low altitudes by solar protons can be expected to alter the conductivity of the atmosphere. Following Cole and Pierce (1965), we define conductivity (λ) as $\lambda = ne\mu$, where n is the number density of charge carriers, e is the carrier charge, and μ is the mobility. The mobility, in turn, is $\mu = e/m\nu$, where m is the carrier mass and ν is the collisional frequency of the carrier against other constituents. Under quasi-equilibrium conditions, the number density of ions is related to the ion-pair production rate by $n = (Q/\alpha_i)^{\frac{1}{2}}$, where α_i is the recombination coefficient between positive and negative ions. Thus, the conductivity can be derived from:

$$\lambda = (e^2/m\nu)(Q/\alpha_i)^{\frac{1}{2}}. \tag{1}$$

To calculate "background" total conductivity profiles representative of quiet conditions as depicted in Figure 3, the production rate (Q) due to cosmic rays (Figure 2) was used along with the loss (recombination) coefficients and collisional frequencies as given by Cole and Pierce (1965). The ionic mass was assumed to be 29, on the basis that the charged carriers are molecular oxygen and nitrogen. There is reason to argue for a larger mass, however, as recent measurements indicate that atmospheric ions in the troposphere and stratosphere are hydrated, with approximately five to seven water molecules attached (Mohnen, 1971). We consider this argument to be relatively unimportant here, but it becomes quite significant in the next section.

The relative abundances of cosmic rays during sunspot maximum and minimum years (Neher, 1967; 1971) account for the difference in quiet time
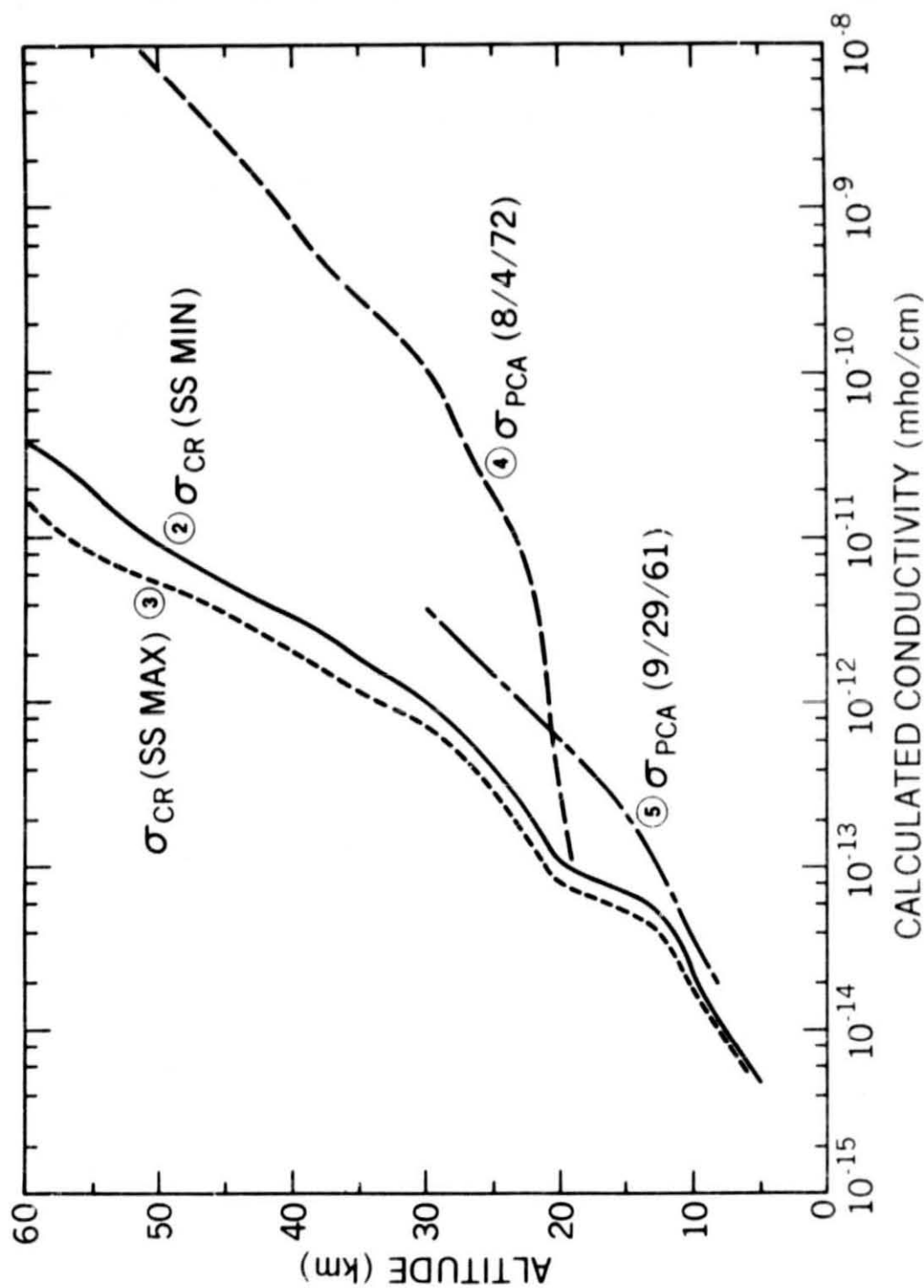
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Figure 3. Atmospheric electrical conductivity profiles derived from and keyed to production rates in Figure 2.

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conductivity profiles given in Figure 3. An incursion of high-energy solar pro-
tons increases the conductivity profile dramatically during disturbed periods,
especially above about 20 km altitude. The August 4 curve (4) in Figure 3 dem-
onstrates the effect of a major solar event; other conductivity profiles appropriate
to less intense events would lie between those for August 4 and for cosmic-ray
background. The unusually hard spectrum observed by Bryant et al. (1962)
produced a conductivity enhancement down to at least 10 km altitude.

It is recognized that the conductivity profiles in Figure 3 can be altered by
making different assumptions regarding the values of collision frequency and
recombination coefficient, both of which are temperature dependent, and regard-
ing atmospheric density which may differ from the standard atmosphere under-
lying the present calculations. Also, as mentioned earlier, the mass of the
charge carriers may be heavier than that employed here. Uncertainties in the
value of these parameters are of secondary importance to the present analysis;
further discussions of their effects on conductivity have been given by others (e.g.,
Hake et al., 1973; Cole and Pierce, 1965). The important point here is that with
a given set of nominally accepted values, an influx of solar protons into the at-
mosphere should drastically alter the conductivity profile at and above about 20 km
altitude. Experimental measurements during PCA's at high latitude (Hale et al.,
1972; Hale, 1974) substantiate this expectation.

Along with copious emission of high-energy solar protons during a solar proton event, the galactic cosmic ray intensity is reduced (the Forbush decrease). In major events a maximum reduction of 30% at ground level is not uncommon, and Pomerantz and Duggal (1973) reported a 50% decrease for the August 4 event. The recovery to predisturbance level can take from one to several days (McCracken, 1963). This decrease is manifest from the ground up to balloon altitudes, and indeed, the fractional decrease near 15 km altitude appears to be 15-20% greater than at ground level (Webber and Lockwood, 1962). Consequently, if cosmic rays were the only ionizing agent, we could expect a decrease in conductivity at altitudes below about 20 km.

The total effect on conductivity of a solar proton enhancement and cosmic ray decrease is illustrated in Figure 4 for the August, 1972 event. The conductivity due to quiet time cosmic ray ionization during solar minimum years from Figure 3 is shown for comparison. Above about 15 km the conductivity exceeds the quiet time value due to solar proton ionization, and below 15 km it is smaller due to the decreased cosmic ray ionization.

The vertical electric field profile (E_h) associated with the disturbed conductivity profile can be calculated from;

$$E_h = J/\lambda_h \tag{2}$$

where J is the air-earth conduction current. The result for the August 4 event is shown in Figure 5. To determine J for this calculation, a quiet-time field of
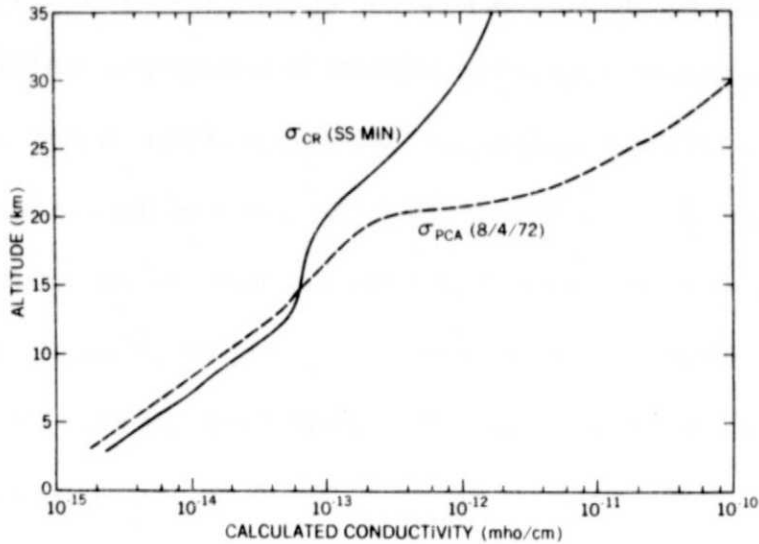
Figure 4. Total effect of the August 4, 1972 solar proton event and cosmic-ray Forbush decrease on the conductivity profile compared to background at solar minimum.
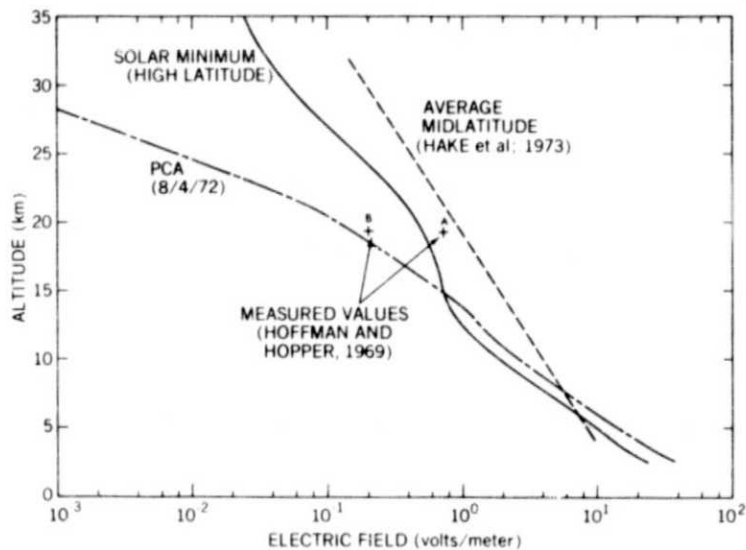

Figure 5. Electric field profiles for August 4, 1972 event, quiet (average) conditions at solar minimum, and an average for midlatitudes as reported by Hake et al. (1973). Points A and B represent electric field measured by Hoffman and Hopper (1969) at constant altitude about 20 minutes apart.

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10 V/m at 5 km altitude (Hake et al., 1973) was used along with the quiet-time conductivity at the same altitude as given by Figure 4. The resulting conduction current of 4.8×10^{-12} amp/m^2 is somewhat higher than the range of values (1 to 3×10^{-12}) discussed by Hake et al. (1973) for mid-latitudes, but it seems reasonable for high latitude where the cosmic ray intensity and consequent conductivity is higher. Assuming this value (4.8×10^{-12}) to be constant with altitude and unaffected by the event, quiet and disturbed day electric field profiles were computed (Figure 5). The validity of this assumption will be examined later.

As expected, the disturbed electric field is decreased above 15 km altitude and enhanced at lower altitudes. The possible reality of this behavior is demonstrated by in situ aircraft measurements. At a constant altitude of 19.5 km, Hoffman and Hopper (1969) measured a mean field of 0.7 V/m which showed fluctuations of about 5% on a time scale of roughly ten minutes (point A in Figure 5). Then, over a period of about 20 minutes the field decreased to 0.2 V/m (point B in Figure 5). The observed decrease of a factor of 3.5 lends credence to the hypothetical decrease computed by the present simplified methods. Also, the increased field at low heights (approximately 60% at 3 km altitude according to Figure 5) is in substantial agreement with the magnitude of enhancements observed by Reiter (1969) atop Zugspitze (2.96 km altitude) in the Bavarian Alps about 2 days after the occurrence of major solar flares. Even though the foregoing analysis is replete with simplifying assumptions and coarse estimates of

atmospheric electric quantities, the results suggest a definite solar–disturbance effect on the atmospheric electric field.

The assumption of an unchanged conduction current during a disturbance is not quite correct, because both Cobb (1967) and Reiter (1969, 1972) have noted increases of 12% to 50% in conduction current following solar flares, more or less concurrent with 30% to 60% increases in electric field strength at 3 km altitude. According to Equation 2, this would mean simply that the low altitude decrease in conductivity could be less than that estimated in the present analysis.

A reason for the reported increase in conduction current might be developed in the following way. In the classical spherical condenser model, where the ground and the electrosphere are the inner and outer plates respectively, the conduction current (also called the air/earth current density) is given by:

$$J = V_H / R_H \tag{3}$$

where V_H is the total potential maintained between the earth and electrosphere (located at height H) by global thunderstorm activity, and the columnar resistance from the earth to the electrosphere is R_H. The latter quantity is defined as:

$$R_H = \int_0^H \frac{1}{\lambda_h} \, dh. \tag{4}$$

Bossolasco et al. (1972) found global thunderstorm activity to increase by 50% about four days after major solar flare eruptions, which implies a similar increase in V_H. Integration of Equation 4 using the conductivity profiles of Figure

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4 indicates that $R_{||}$ would decrease by only one to two percent during an event of the August 4 magnitude. Thus, the main observed increase in J, according to Equation 3, would be due to the increase in $V_{||}$. The resultant increase in electric field strength at low heights could therefore be due to the combined influence of decreased conductivity below about 15 km height and increased conduction current from Earth to the electrosphere.

Details of particular events may well differ from each other and from the above-sketched typical sequence due to differences in solar proton acceleration mechanisms, solar magnetic shielding effects on cosmic rays near the Earth, and anisotropies in incoming cosmic rays (c.f., Dutt et al., 1973), all of which would affect the temporal and spatial distribution of the atmospheric effects. On the whole, however, it appears that the sequence of atmospheric electric variations parallel those of the associated solar-proton and cosmic-ray phenomena. The manner in which the changes in atmospheric electric parameters may initiate thunderstorm development is examined in the next section.

3. THUNDERSTORM INITIATION: PROPOSED MECHANISM

The foregoing analysis concerns changes in the "fair-weather" atmospheric electric picture. In order to explain correlations between solar-related disturbances and thunderstorm activity, it is necessary to link solar-induced changes in the atmospheric electric parameters to thunderstorm development. Noting that "the thunderstorm represents the final phase of weather phenomena, which are

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connected with vertically upwards moving moist air masses..." (Israel, 1973, p. 517), it is tempting to believe that the establishment of this link will also shed light on a way clouds might produce precipitable water drops resulting in rain showers unaccompanied by lightning discharge phenomena.

Since the electric field in a thunderstorm is of the order of 10^5 V/m (c.f., Mason, 1972), it is evident that the field changes of ~60% in the low atmosphere, based on a quiet field of the order of 10 V/m, can only serve as a trigger. When meteorological conditions are receptive to thunderstorm development (strong updrafts with moist air present), an initiation of charge separation through solar-controlled changes in atmospheric electric parameters may be sufficient to begin the development. A mechanism by which this process might proceed is suggested below. The qualitative model to be described relies on a combination of an enhanced flux of high-energy solar protons penetrating to the stratosphere and upper troposphere coupled with a decreased cosmic ray flux, both of which are associated with active solar events.

Although thunderstorm electrification is not completely understood, it is possible to describe a thundercloud model having attributes common to most extant theories. It is generally agreed (c.f., Mason, 1972; Israel, 1973) that an excess of positive charge exists at the top of the thundercloud and an excess of negative charge is found near the base of the cloud. Sometimes there is a smaller region of positive charge below the main region of negative charge. In this

classical model of charge distribution, between the two main charge centers the polarity is mixed, as depicted in Figure 6. The negatively charged screening layer discovered by Vonnegut et al. (1966), using aircraft measurements above the cloud top, represents in our view, an addition to the classical model, and provides the key to our proposed initiation mechanism.

There has been considerable speculation regarding the charging mechanisms which might provide the classical distribution sketched in Figure 6 and subsequently build up the intense electric fields required for lightning discharge (c. f., Mason, 1972, 1976; Sartor, 1961, 1967; Levin and Ziv, 1974; Ziv and Levin, 1974; Kamra, 1970, 1975, 1976; Gunn, 1954; Moore, 1974, 1976; Griffiths et al., 1974; Griffiths and Latham, 1975; Griffiths, 1976; Paluch and Sartor, 1973). Implicit to all the theories is the necessary assumption that the whole process somehow gets started, but there have been few explicit attempts to explain the triggering or initiation mechanisms. (Sartor (1967), however, has suggested that the initial electrification might be provided by the fair weather charge distribution of the atmosphere.) The main thrust of the present effort is therefore to define a physically plausible initiation mechanism which is linked to solar activity, in order to explain the reported statistical correlations between thunderstorm occurrence and solar activity (Section 1).

We begin with the eruption of a major solar flare with its associated injection of high energy solar protons into the stratosphere. The solar protons

CHARGED
SCREENING LAYER
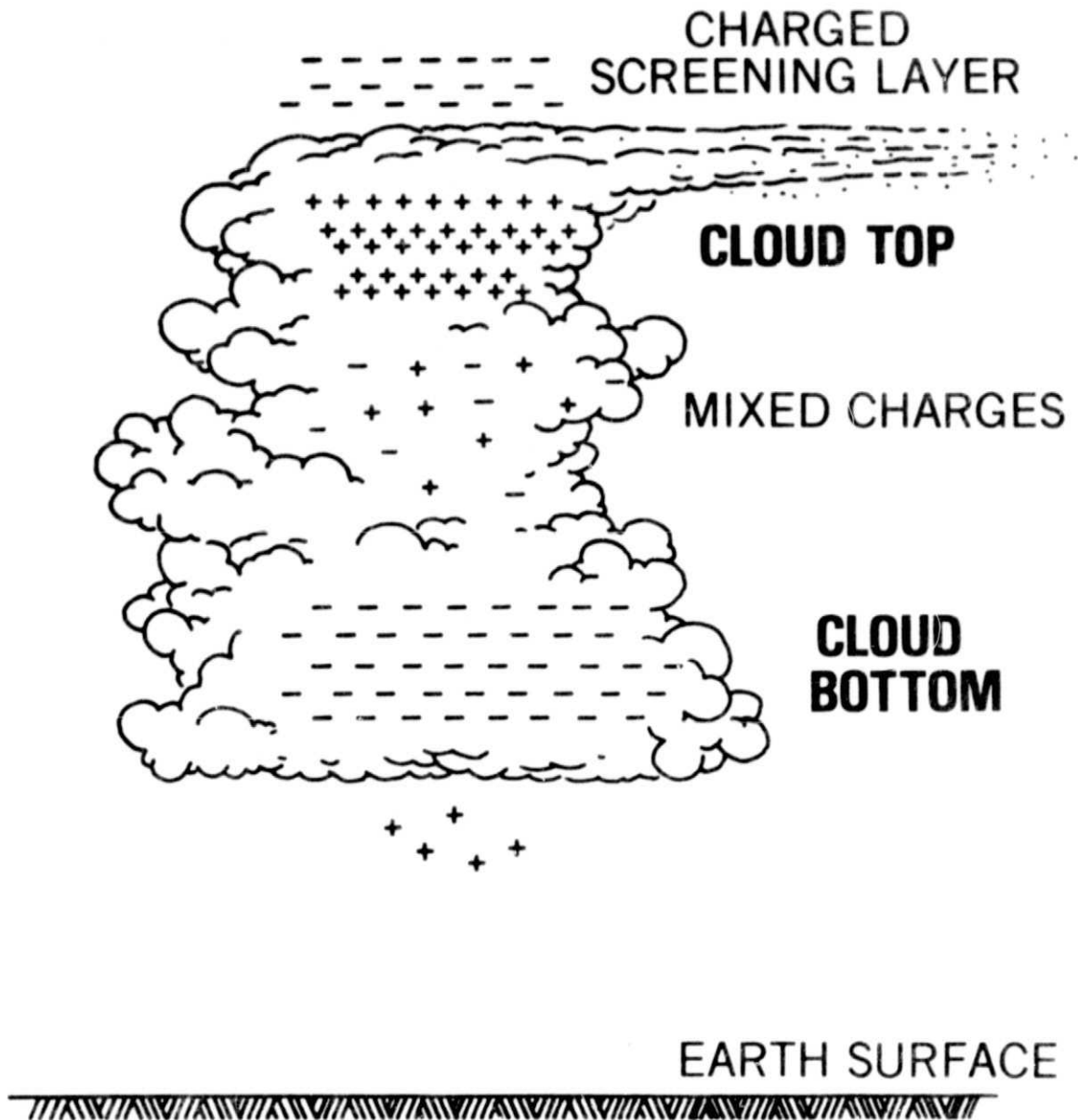
CLOUD TOP

MIXED CHARGES

CLOUD
BOTTOM

EARTH SURFACE

Figure 6. A model of charge distribution in a thundercloud. The "classical model" is contained within the cloud outline, and the negatively charged screening layer is added on basis of results by Vonnegut et al. (1966).

produce additional ionization down to at least 20 km altitude and sometimes lower
(Section 2). The ion pairs so produced consist initially of an electron and a posi-
tive ion, but at these low heights the electron immediately attaches to a neutral
constituent to create a negative ion. It is assumed that the electron attachment
preferentially goes with hydrated species so that the negative ions are heavier
than the positive ions and thereby have less mobility. (This crucial assumption
is examined in the next section.) Under the influence of the downward-directed
fair weather electric field the more mobile positive ions will be driven to lower
heights until the upward-directed local field between the positive charges and the
negative screening layer just balances the fair weather field.

In the next stage of initiation development, the Forbush decrease in cosmic
ray intensity would decrease the conductivity and thereby increase the electric
field at heights below about 15 km (Section 2). This increased field toward ground
would promote coalescence and produce larger particles (Levin and Ziv, 1974)
carrying predominantly negative charge. These larger particles fall under the
influence of gravity to a lower height where their downward motion would be in-
hibited by both bouyant forces and the electric field from the positive space
charge center. This action would complete the pattern for initial charge distri-
bution required for a thundercloud (i. e. , Figure 6).

At this point, the concentration of charge at the levels of cloud top and bot-
tom would still be too small to produce the intense fields required for lightning

discharge, but a continuation of the solar proton influx and Forbush decrease over a period of a few days would serve to strengthen this distribution pattern. Additionally, the larger ions with reduced mobility would further decrease the conductivity within the cloud region leading to still higher electric fields, and the increased potential gradient would promote still more coalescence. As a result, the modified charge distribution and enhanced electric field could well serve to initiate the required electrified cloud growth leading to thunderstorm development as envisioned by Sartor (1967). If, as Sartor's (1967) model suggests, a higher initial electric field promotes easier and more rapid growth of the thundercloud, then the 60% field enhancement generated by the present model might make the difference between the occurrence of a convective rain shower without lightning and a fully developed thunderstorm.

4. JUSTIFICATION AND DISCUSSION

In the formulation of the foregoing initiation mechanism, it is evident that a number of assumptions had to be made. Here it is attempted to justify the more important ones, and to elaborate on other ramifications of the model.

Possibly the most crucial assumption is that the electrons from the proton-produced ion pairs preferentially attach to hydrated species. The attachment rates between electrons and the various atmospheric constituents are not known at the lower altitudes, so it is necessary to use an indirect argument. Under normal, or equilibrium conditions, the number of positive ions in the height

range of approximately 4 to 25 km exceeds that of the negative ions (c.f.,

Paltridge, 1965; 1966), but the positive and negative conductivities are nearly equal.

This implies that the mobility of the negative ions is less than that of the positive

ions. Also, according to the atmospheric chemical reaction chains postulated

by Mohnen (1971), the terminal ions are hydrated with n water molecules. The

positive ions are $H^+ \cdot (H_2O)_n$, and the largest percentages have n = 7 at 5 to

10 km altitude, n = 6 at 20 km and n = 5 at 30 km. The terminal negative ions

are $NO_3^- \cdot (H_2O)_n$, but the number of water molecules attached is uncertain. If,

however, the value of n is similar for both positive and negative ions, it is evi-

dent that the negative ions, being heavier, will have a smaller mobility. It is

presumed that under fair weather conditions these positive and negative charge

carriers would coexist at all heights (at least below about 30 km) to maintain

electrical neutrality, since ordinarily there is little evidence for space charge

regions (Hake et al., 1973). The excess ionization introduced by solar protons

would, however, institute charge separation as described in the preceding sec-

tion, and produce a positive space charge center at some altitude below the neg-

ative screening layer.

As is evident in Section 2, the injection of excess ionization by solar protons

is generally most pronounced at about 20 km height and upwards, whereas the

tops for most thunderclouds are seldom observed above 15 km height. Assuming

a cloud top height of 10 km, it appears that the charge-separated ionization would
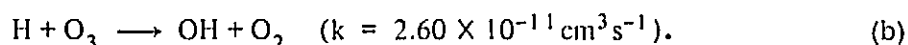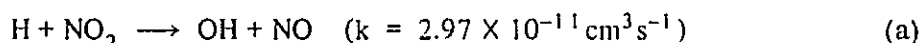
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need to be transported downward a distance of about 10 to 20 km to place it in a position commensurate with extant thundercloud charge distribution models. With a mobility of the order 1 m/sec per V/m (Hake et al., 1973) and a field of about 0.1 V/m at 20 km height (Figure 5), the ion velocity would be 0.1 m/sec. The time required for the downward transport thus would be roughly 10^5 to 2×10^5 sec, or one to two days. This delay, coupled with the lag of one to two days between solar flare eruption and maximization of the Forbush decrease, would lead to the observed 2-4 day delay between the flare occurrence and increased thunderstorm activity reported by Reiter (1969) and Bossolasco et al. (1972).

Two additional factors associated with the proton influx may serve to enhance the initial triggering process proposed here. One is the question of what happens to the solar protons after they have become thermalized in the lower atmosphere. They are, after all, hydrogen ions, and when a proton captures an electron it becomes a neutral hydrogen atom. We suggest that those existing as thermalized hydrogen ions will become hydrated and add to Mohnen's (1971) population of $H^+ \cdot (H_2O)_n$, and under the action of the atmospheric electric field, also add to the positive space charge center at the cloud top level.

Those thermalized protons which capture an electron and become free hydrogen atoms may ultimately enter a scheme recently proposed by Dickinson (1975). According to Dickinson, cloud droplets are unlikely to be nucleated directly by ionization, and he suggests that instead, stratospheric aerosols produced by the

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ionization could serve as condensation nuclei. In his view, the major strato-
spheric aerosol is a sulfuric acid-water mixture. The sulfuric acid aerosol
greatly lowers the saturation vapor pressure of water over its pure value, and
according to Dickinson, it may be the dominant nucleating agent of clouds just
above and below the tropopause in middle and high latitudes. The association
between solar events and the H_2SO_4 aerosol required in Dickinson's theory could
be provided by a chain of chemical reactions involving the hydrogen atoms yielded
by the thermalized protons.

Two important reactions would be (Shimazaki and Whitten, 1976):

$$H + NO_2 \longrightarrow OH + NO \quad (k = 2.97 \times 10^{-11} cm^3 s^{-1}) \tag{a}$$

$$H + O_3 \longrightarrow OH + O_2 \quad (k = 2.60 \times 10^{-11} cm^3 s^{-1}). \tag{b}$$

The formation of sulfuric acid would then proceed principally by (Davis, 1974):

$$2OH + SO_2 \longrightarrow H_2SO_4. \tag{c}$$

In reaction (c) the OH molecules are supplied by reactions (a) and (b), and the
SO_2 presumably comes up from the ground. A number of other reactions are
available for depleting H (Shimazaki and Whitten, 1976), but their reaction rates
(k) are either slower than (a) and (b), or the reactions do not lead to the forma-
tion of H_2SO_4. Some of the OH molecules from these two reactions might com-
bine with ozone to yield $HO_2 + O_2$ with a rate of 1.7×10^{-14}, but the HO_2 would
also oxidize sulfur dioxide to produce H_2SO_4 (Davis, 1974).

Whether or not these two additional factors would be significant depends upon the magnitude of the thermalized proton contribution to the total hydrogen population. To obtain a rough guess, let us assume that all protons stopping at altitudes below the atmospheric electric equalization layer (approximately 50 km) will be subject to downward migration due to the atmospheric electric field as long as they remain hydrogen ions. The energy of the protons meeting this stopping criterion is $E \geqslant 30\,MeV$ (Reid, 1974). For the solar-disturbed period from August 4, 1972, 0700 UT to August 7, 1972, 1500 UT, the integrated flux of solar protons with $E \geqslant 30\,MeV$ was $8 \times 10^9\,cm^{-2}$ (Kohl and Bostrom, 1973). After a certain passage of time these protons could be distributed equally from 0 km to 50 km altitude, and thus have an average number density of $1.6 \times 10^3\,cm^{-3}$.

By contrast, the number density of neutral hydrogen [H] is approximately $10^{-1}\,cm^{-3}$ at 20 km and 10^6 at 50 km, according to several atmospheric models reviewed by Shimazaki and Whitten (1976). These models can be approximated by an analytical expression of the form:

$$[H] = K\exp(h/h_0) \tag{5}$$

where K and h_0 are constants evaluated from the data, which can be used to determine an average number density of 3.2×10^2 in the height range 20–50 km. Thus, it is conceivable that the thermalized protons, having been transformed to hydrogen atoms by electron capture, could increase the hydrogen density by a factor of 5 or even more at the lower altitudes.

Although not strictly germane to the present argument, it may be of interest to digress a moment to consider a final point of discussion. It is generally agreed that the Earth's potential gradient is proportional to the number of thunderstorms in progress (c.f., Israel, 1973, p. 365), but the question of whether increased thunderstorm activity is the cause or the result of an increase in atmospheric electric field (potential gradient) has not really been resolved. Consideration of the morphology of apparent atmospheric responses to solar activity may shed some light on this question. In a typical sequence beginning with a major solar flare eruption, the conductivity would begin to increase (and the potential gradient to decrease) at altitudes at and above about 20 km approximately one to three hours later due to the arrival of high energy solar protons, and continue to be enhanced (electric field depressed) for one to five days, or as long as the solar proton bombardment persisted. There would, of course, be variations in magnitude marked by a maximum some 3 to 12 hours after flare beginning and a gradual recovery to pre-flare conditions as the proton flux decayed. About one day after the flare eruption the conductivity below about 15 km height would start to decrease with an attendant increase in potential gradient due to the Forbush decrease in cosmic ray intensity as measured at the ground (McCracken, 1963). Minimum conductivity (and maximum potential gradient) would be reached approximately 8 hours after the start of the Forbush decrease, with a gradual return to pre-flare conditions over the next 2 to 4 days. Thus, the action of the Forbush decrease would tend to maximize the potential gradient (at heights below 15 km)

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one to two days after the solar flare occurrence. A superposed epoch analysis of Zugspitze data for March 1966–July 1968 (Reiter, 1971) showed that the potential gradient began increasing about one day after the occurrence of proton and H_α flares and maximized two to three days after the flare, in keeping with the presently suggested Forbush-decrease effect.

By contrast, enhanced world-wide thunderstorm activity (Bossolasco et al., 1972) and European thunderstorm occurrence (Reiter, 1969) maximize about 4 days after the flare occurrence, or about two days after the maximum in potential gradient. From these statistics it appears that the potential gradient increases first, followed later by increased thunderstorm activity, and one may conclude that the activity is the result rather than the cause of the increased potential gradient.

5. SUMMARY AND CONCLUSIONS

The proposed initiation mechanism provides a way for solar activity to trigger thundercloud development through the combined action of solar protons producing excess ionization at and above about 20 km altitude and cosmic-ray intensity decreases producing decreased conductivity and field enhancement at lower heights.

The fair-weather electric field forces charge separation of the proton-generated ion pairs provided that the electrons attach preferentially to hydrated

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(i.e., heavier) atmospheric molecules, to create a negative screening layer and an excess positive charge region at some height below it.

At heights still lower than the positive charge region, the enhanced field due to lowered conductivity promotes coalescence and the formation of negatively charged droplets which are heavier than those in the negative screening layer. These are therefore pulled downward by gravity to a level where buoyant and electrical forces suspend them, which completes the sequence leading from the solar-related phenomena to an atmospheric electric charge distribution agreeable with extant models of the distribution in thunderclouds.

There may also be promotion of cloud nucleation through a lowered saturation vapor pressure introduced by H_2SO_4 (Dickinson, 1975) which might be formed from chemical reactions involving thermalized solar protons, although this is speculative at this time.

Beyond the initial electrification, additional processes outside the purview of this paper must be invoked to explain the buildup of intense electric fields capable of producing lightning discharges.

On a short-term basis, this linking mechanism would obtain following major solar flare eruptions, and thereby explain reported correlations of thunderstorms with flare occurrence (Bossolasco et al., 1972) and with the appearance of active sunspot groups on the solar surface (Flohn, 1951). The solar cycle variation in

which more thunderstorms occur during maximum years than minimum years follows because in the former years there are many more active sunspot groups, and major solar flares with associated high-energy proton emission occur with a frequency about 7-1/2 times greater than during minimum years (Dessler, 1975).

Because of the difficulty in verifying the several assumptions regarding basic quantities and processes, it can only be tentatively concluded that the proposed mechanism triggers thunderstorms in high latitudes. The mechanism is, however, supported by previously reported correlations between solar activity and thunderstorm occurrence in northern latitudes and by established atmospheric electricity concepts. Considerable additional investigation would be required to determine if a similar mechanism might be involved in triggering the much more frequent occurrence of thunderstorms in low latitudes.

It is concluded, therefore, that attempts to obtain experimental verification of the proposed trigger would be worthwhile. A coordinated effort would be required, involving satellites to monitor solar proton influxes, ground and balloon measurements of cosmic ray intensities, determination of the electric fields and charge distributions in the atmosphere and their charges throughout the course of solar events, and perhaps most importantly, identification of charge carrier species along with their mass and size distributions. One important question to be answered would relate to the lifetime of the redistributed charge between PCA events, something for which no information exists at this time.

In the meantime, laboratory and other experimental studies should be made to determine relative attachment rates between electrons and light ions on the one hand, and heavy hydrated ions or water droplets on the other. A further elucidation of the role played by electric fields in promoting coalescence would also be helpful.

ACKNOWLEDGMENTS

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